

Formation of Black Hole Low-Mass X-ray Binaries

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Abstract

The majority of known Galactic black holes reside in low-mass X-ray binaries. They are rare and fascinating objects, providing unique information on strong gravity, accretion disc physics, and stellar and binary evolution. There is no doubt that our understanding of the formation of black hole low-mass X-ray binaries has significantly advanced in the past decade. However, some key issues are still unresolved. In this paper we briefly summarize the observational clues and theoretical progress on the formation of black hole low-mass X-ray binaries.

Keywords:

Black holes, X-ray binaries, Accretion.

1. The Galactic black hole X-ray binaries

Stellar evolution predicts that black holes (BHs) form from massive stars with mass $\gtrsim 20M_{\odot}$ (e.g., Fryer et al. 2012, and references therein), and that there are more than 10^8 BHs in the Galaxy (e.g., van den Heuvel 1992). However, only BHs in X-ray binaries can be detected through accretion.

Currently there are 24 X-ray binary systems in which the BHs have been confirmed via dynamical observations (Remillard & McClintock 2006; Charles & Coe 2006; Casares & Jonker 2014). Five of them possess O or B type companion stars and belong to high- and intermediate-mass X-ray binaries. In the remaining 19 binaries the companion stars are of relatively low mass ($\lesssim 2M_{\odot}$), and these binaries are transient X-ray sources with episodic outbursts, which are likely to be caused by thermal and viscous instabilities in

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an accretion disc around the BH (van Paradijs 1996; King, Kolb, & Burderi 1996; Dubus et al. 1999; Lasota 2001)¹. The main properties of the BH (candidate) low-mass X-ray binaries (LMXBs) can be summarized as follows.

(1) The orbital periods

While a few BHLMXBs (e.g., XTE J1550–564, GX339–4, GS2023+338, GRS1915+105, GS 1354–64, GROJ1655–40, 4U1543–47) have orbital periods P_{orb} longer than 1 day, others are compact binaries with $P_{\text{orb}} < 1$ day. MAXI J1659–152 is the shortest period BH candidate binary known to date, with a period of 2.414 ± 0.005 hr (Kuulkers et al. 2013). Observations also show that XTE J1118+480 and A0620–00 are undergoing rapid orbital decay at a rate $\dot{P}_{\text{orb}} = -1.90 \pm 0.57$ ms yr^{−1} and -0.60 ± 0.08 ms yr^{−1}, respectively (González Hernández et al. 2012, 2013).

(2) The companion stars

In the majority of the binaries, the donor companions are dwarf stars with spectral types ranging from A2V to M1V; there are a few cases in which the donors are giants or subgiants (e.g., K1/5III for GRS1915+105, K0-K3IV for V404 Cyg, B9III for XTE J1819.3–2525, F3-G0V for GRO J1655–40, and K2/4IV for XTE J1550-564) (Casares & Jonker 2014, and references therein). These properties suggest that most of them are low-mass stars (less than $1 M_{\odot}$). For those in which the lithium abundance was measured (GS 2000+25, A0620–00, and Nova Mus 91), observations show the excess above the solar value by a factor of about 20 – 200 (Martin et al. 1992, 1994, 1996).

(3) The X-ray luminosities

A typical BHLMXB spends most of its time in quiescence, and occasionally exhibit outbursts during which its luminosities increase by several orders of magnitude. During outbursts the X-ray luminosities rise to $\sim 10^{37} - 10^{39}$ ergs^{−1}; between outbursts, they remain in a “quiescent” state, with typical X-ray luminosities below $\sim 10^{32}$ ergs^{−1}, except V404 Cyg, which has a much brighter quiescent luminosity, around a few times $\sim 10^{33}$ ergs^{−1} (Chen, Shrader, & Livio 1997; Garcia et al. 2001; Wu et al. 2010).

(4) The BH masses and spins

Astrophysical BHs are characterized by mass and spin. Dynamical mass

¹While the thermal/viscous instability can explain the main features of X-ray outbursts in a general way, there are phenomena which are clearly not in agreement with that picture. See Lasota (2001) and Maccarone (2014) for more detailed discussion.

determinations have been made in 17 BHLMXBs, with the BH mass ranging from $\sim 2.7 M_{\odot}$ to $\gtrsim 15 M_{\odot}$ (Casares & Jonker 2014, and references therein). Statistical studies on the mass distribution of neutron stars (NSs) and BHs (Bailyn et al. 1998; Özel et al. 2010; Farr et al. 2011) suggest the presence of a mass gap or dearth of compact objects in the interval $\sim 2 - 5 M_{\odot}$ (see however, Kreidberg et al. 2012). Numerical simulations of supernova (SN) explosions typically generate a continuous distribution of BH masses that decays with mass (Fryer 1999; Fryer & Kalogera 2001). The paucity of BHs with masses less than $5 M_{\odot}$ is probably related to the physics of SN explosions that lead to the formation of BHs (Fryer et al. 2012; Belczynski et al. 2012).

The spins of nearly 20 BHs have been estimated (McClintock, Narayan, & Steiner 2014; Fabian et al. 2014, and references therein), by means of X-ray continuum-fitting (Zhang, Cui, & Chen 1997; Davis et al. 2005) and modeling relativistic reflection (Fabian et al. 1989). The measured spins for BHs in LMXBs range from 0.12 ± 0.19 (for A0620–00, Gou et al. 2010) to > 0.98 (for GRS 1915+105, McClintock, Shafee, & Narayan 2006; Miller et al. 2013). However, one needs to caution that both methods are model dependent to some extent, and the results obtained for the same sources do not always agree each other.

2. The standard model for the formation of BHLMXBs

All Galactic BHLMXBs dynamically confirmed are found in the Galactic field with no apparent nearby dense clusters, so dynamical interactions (i.e., tidal capture and exchange encounter) are not likely to occur during their formation processes². The standard scenario for the LMXB formation (van den Heuvel 1983; Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2006) starts with a detached primordial binary with an extreme mass ratio in a relatively wide orbit. Since most of the BHLMXBs are compact binaries with orbital periods less than 1 day, there must exist a process that leads to significant orbital decay of the primordial binary. After the massive primary star evolves off the main sequence, its radius rapidly increases, initiating Roche lobe overflow. The mass transfer proceeds on a dynamical timescale

²There are several quiescent BH candidates discovered from radio studies in globular clusters (Strader et al. 2012; Chomiuk et al. 2013), but these are not yet dynamically confirmed.

since the primary star is much more massive than the secondary. The secondary star spirals into the stellar envelope when the massive star engulfs it. This is the so-called common envelope (CE) phase (Paczynski 1976). The binary orbit changes dramatically since the orbital energy is lost due to friction between the secondary star and the envelope of the primary, and part of the lost orbital energy is used to eject the envelope. Depending on whether the energy dissipated is enough to expel the envelope, the CE evolution will result in either a merger of the secondary star and the core of the primary, or a close binary consisting of the secondary star orbiting around the naked core of the primary star (see Taam & Ricker 2012; Ivanova et al. 2013, for recent reviews of CE evolution). In the latter case, as the duration of the CE phase is very short (probably less than a few hundred years), the secondary, which is still relatively unevolved, is assumed to remain intact. The core continues its evolution towards core collapse to form a BH. The binary orbit is altered due to mass loss during the core collapse and possibly an natal kick is imparted to the BH. If the binary survives all these stages, the secondary star will evolve and overflow its Roche lobe, due to either nuclear expansion or orbital angular momentum loss caused by magnetic braking (MB) and/or gravitational radiation. Mass transfer onto the BH leads to the formation of a LMXB. In the former case the binary will evolve with increasing orbital periods, while in the latter, a converging system is formed until the donor becomes degenerate. If the mass transfer proceeds at a sufficiently low rate, thermal and viscous instability may occur in the accretion disc around the BH, leading to transient behavior. Based on the spatial distribution and recurrence times of known BHLMBs, Wijers (1996) and Romani (1998) estimated that there may be ~ 2000 such systems in the Galaxy.

There are several unresolved issues in the standard scenario, which are outlined as follows. (1) The secondary star, because of its low mass, may not have enough energy to eject the envelope of the BH progenitor during the CE phase, unless a significant fraction of the envelope has been previously lost through a very efficient stellar wind; (2) The primary star may lose a large fraction of its mass during the SN explosion that produced the BH, and that may disrupt the binary. To show the former in some detail, we use the standard energy conservation equation (Webbink 1984) to deal with the CE evolution,

$$\alpha_{\text{CE}} \left(\frac{GM_{1,\text{f}}M_2}{2a_{\text{f}}} - \frac{GM_{1,\text{i}}M_2}{2a_{\text{i}}} \right) = -E_{\text{bind}}, \quad (1)$$

and

$$E_{\text{bind}} = -\frac{GM_{1,i}M_{1,\text{env}}}{\lambda R_{1,\text{lobe}}}, \quad (2)$$

where M_1 and M_2 are the primary and secondary masses respectively, a the orbital separation of the binary, $M_{1,\text{env}}$ the mass of the primary's envelope that is ejected from the system during the CE evolution, $R_{1,\text{lobe}}$ the Roche-lobe radius of the primary at the onset of overflow, and the indices i and f refer to the initial and final stages of the CE evolution respectively. The parameter λ includes the effect of the mass distribution within the envelope, and the (possible) contribution from the internal energy (de Kool 1990; Dewi & Tauris 2000), and α_{CE} is the CE efficiency with which the orbital energy is used to unbind the stellar envelope. As pointed out by Justham et al. (2006), Eqs. (1) and (2) lead to the lower limit for the parameter λ in order to avoid a merger of the primary's core and the secondary

$$\lambda \gtrsim 0.15 \alpha_{\text{CE}}^{-1} \left(\frac{R_{1,\text{max}}}{2300 R_{\odot}} \right)^{-1} \left(\frac{M_{\odot}}{M_2} \right)^{1/2}, \quad (3)$$

where $R_{1,\text{max}}$ is the maximum stellar radius of the BH progenitor. Thus, for a secondary with $M_2 \lesssim 1 M_{\odot}$, λ must be at least ~ 0.15 . However, calculations by Podsiadlowski et al. (2003) show that stars of mass $M_1 > 25 M_{\odot}$ have $\lambda < 0.1$ for all $R_1 > 300 R_{\odot}$, even when all the energy of recombination for the ionized species in the envelope that can be liberated to aid the CE ejection process is included. Therefore, ejection of the massive envelope of a BH progenitor by a low-mass star proves rather difficult if not impossible. This fact has been noted by Portegies Zwart, Verbunt, & Ergma (1997). Assuming $\alpha_{\text{CE}}\lambda = 0.5$, these authors showed that the parameter space of the semi-major axis of the primordial binary for the survival of the spiral-in process is extremely small, so that the predicted birth rates are about two orders of magnitude lower than derived from observations. Kalogera (1999) also argued that abnormally high values of the efficiency parameter α_{CE} are required to gain any agreement with the observationally inferred BHLMBX birth rate (see also Kiel & Hurley 2006; Yungelson & Lasota 2008, for similar investigations).

3. Modified models

3.1. Intermediate-mass companions

As seen from Eq. (3), if the secondary stars are of intermediate mass (i.e. $\sim 3 - 5 M_{\odot}$), they would be more likely to eject the envelope. This

mens that at least part of LMXBs may evolve from intermediate-mass X-ray binaries (IMXBs), when the donor mass becomes $< 1 M_{\odot}$ due to mass transfer. During the IMXB phase, since mass is transferred from the less massive secondary to the more massive BH (usually of mass $> 5 M_{\odot}$), the binary orbit increases accordingly. This can naturally explain the formation of the long-period systems like GRS 1915+105 (Podsiadlowski et al. 2003), but poses a problem for the short-period systems. Obviously an efficient mechanism for orbital angular momentum loss is required for the formation of compact BHLMXBs.

Although intermediate-mass stars are not thought to be subject to MB, Justham et al. (2006) proposed that the secondary stars may be initially Ap or Bp stars, which are known to possess anomalously strong ($\sim 10^2 - 10^4$ G) magnetic fields (Moss 1989; Braithwaite & Spruit 2004). Combining with the assumption that a substantial stellar wind may be driven from the donor star by the flux of X-ray radiation that is produced by accretion onto the BH, they showed that intermediate-mass donor stars with an anomalous magnetic field (with $B \gtrsim 10^3$ G) can be braked sufficiently to form short-period systems.

Chen & Li (2006) proposed an alternative way of angular momentum loss from IMXBs. They assumed that a small fraction (δ) of the transferred mass from the donor star during the RLOF may not accrete onto the BH, but leave the binary and form a circumbinary disc. The tidal torques exerted by the disc can effectively drain orbital angular momentum from the binary (Spruit & Taam 2001; Taam & Spruit 2001). It was shown that with $\delta \sim 0.01 - 0.1$ (depending on the initial orbital periods), a circumbinary disc can cause secular orbital shrinking, leading to the formation of compact BHLMXBs; for smaller δ , the orbits always expand during the evolution. It is interesting to note that Munro & Mauerhan (2006) have detected excess mid-infrared radiation from A 0620-00 and XTE J1118+480 with an emitting areas ~ 2 times larger than the binary orbital separations, providing possible evidence of the existence of a circumbinary disc around some BHLMXBs. However, Gallo et al. (2007) suggested that synchrotron emission from a partially self-absorbed outflow might be responsible for the observed mid-IR excess, in place of, or in addition to, thermal emission from the circumbinary material.

Support of the IMXB models comes from the CNO-processed material seen at the surface of XTE J1118+480 from the ultraviolet spectra (Haswell et al. 2002). This means that the companion star must be partially nuclear-evolved and have lost its outer layers, exposing inner layers which have been mixed

with the CNO-processed material from the central nuclear-burning region. Mass transfer must therefore have been initiated from a somewhat evolved donor of initial mass $M \gtrsim 1.5 M_\odot$ (Fragos et al. 2009).

However, the effective temperatures of the model donor stars are significantly higher than for those of the observed donor stars in BHLMXBs (Justham et al. 2006). The problem results from the fact that, even though the initially intermediate-mass star loses much of its mass fairly rapidly, the star is still somewhat evolved chemically (both in helium and in CNO abundance) by the time its mass has been reduced to $\sim 1 M_\odot$. This keeps the donor stars hotter than observed.

Another important clue on the initial mass of the secondary can be derived from the spin of the BH. As the BH accretes mass and angular momentum, its spin parameter ($a \equiv cJ/GM^2$) increases according to (Bardeen 1970; Thorne 1974; King & Kolb 1999),

$$a = \left(\frac{2}{3}\right)^{1/2} \left(\frac{M_{\text{BH}}^0}{M_{\text{BH}}}\right) \left\{ 4 - \left[18 \left(\frac{M_{\text{BH}}^0}{M_{\text{BH}}}\right)^2 - 2 \right]^{1/2} \right\} \quad (4)$$

for $M_{\text{BH}} < \sqrt{6}M_{\text{BH}}^0$. Here M_{BH}^0 and M_{BH} are the initial and current masses of the BH, respectively. If the BH spin in LMXBs is acquired through accretion after its formation, one may estimate the accreted mass ($\Delta M = M_{\text{BH}}^0 - M_{\text{BH}}$) by the BHs and the possible initial mass range the secondary from the measured BH mass and spin. That can provide useful constraints on the properties of the progenitor binaries. This idea can be tested for any arbitrary BHLMXB by comparing the derived BH spin based on the orbital period and the spectral class of the donor star with the measured one. It may also help recover the “true” birth mass distribution for BHs from the current one (e.g., Fragos & McClintock 2015).

Therefore it seems that, the survival of CE evolution seems to require that the secondary be initially of intermediate mass, while the apparent donor spectral classes imply that the secondary would be of low mass at the onset of the Roche lobe overflow. A plausible solution to this puzzle is that the secondary may be initially an intermediate-mass star, but lose a significant part of its mass after the formation of the BH, probably due to the ejecta impact during an aspherical SN (Li 2008)³. The ablated secondary star could

³ The supersolar abundances of Mg, Al, Ca, Fe and Ni in the atmosphere of the

then become a low-mass star, and MB would shrink the binary orbit and drive mass transfer, producing a compact BHLMB.

3.2. CE evolution

Podsiadlowski et al. (2003) found that the values of λ that are appropriate to stars in the mass range $(25 - 45)M_{\odot}$ and the later phase of their evolution (i.e., in or beyond the Hertzsprung gap) lie in the range of $0.01 \lesssim \lambda \lesssim 0.06$. These values were obtained under the following assumptions: (1) the definition of λ includes the gravitational binding energy, the thermal and the ionization energy within the envelope (Han et al. 1994; Dewi & Tauris 2000); (2) the core mass in the primary star is defined as the central mass that contains $1M_{\odot}$ of hydrogen, and (3) the primary star loses mass through stellar wind at a rate according to the prescription of Nieuwenhuijzen & de Jager (1990). Since CE evolution plays a key role in the formation of these systems, in the following we will discuss each point in some detail.

Besides the thermal and ionization energy, other energy sources may also contribute to the envelope ejection. One of them is nuclear fusion (Ivanova 2002). This can occur during the slow merger of a massive primary with a secondary of mass $\sim 1 - 3M_{\odot}$, when the primary has already completed helium core burning. Podsiadlowski et al. (2010) suggested that, once the inspiraling secondary fills its own Roche lobe during the CE phase, a stream of hydrogen-rich material from the secondary can penetrate deep into the primary's core, mixing hydrogen into the helium-burning shell, and leading to a thermonuclear runaway. The released nuclear energy (\gtrsim a few times 10^{50} ergs) during this explosive hydrogen burning could exceed the binding energy of the helium shell, and result in the explosive ejection of both the hydrogen and the helium layers, producing a close binary containing a CO star and a low-mass companion. The subsequent evolution then leads to a compact BHLMB. This scenario also suggests that the formation of BHs in this kind of systems could have been accompanied by long-duration gamma-ray bursts.

Ivanova & Chaichenets (2011) pointed out that the usually adopted energy criterion for the CE phase is not sufficient for an envelope ejection. They argued that mass outflows are likely to occur during the slow spiral-in stage, and the condition for such outflows is to balance the orbital energy with the

companion stars of GRO J1655–40 (Israelian et al. 1999; González Hernández et al. 2008) and XTE J1118+480 (González Hernández et al. 2006) suggest that these BHs are likely to form in a SN event.

enthalpy of the envelope rather than merely the internal energy. This is to add a pressure/density (P/ρ) term in the binding energy equation

$$E_{\text{bind}} = - \int_{\text{core}}^{\text{surface}} [\Psi(m) + \epsilon(m) + P(m)/\rho(m)] dm, \quad (5)$$

where Ψ is the gravitational potential energy, and ϵ is the specific internal energy. Since P/ρ is non-negative, the condition to start outflows occurs before the envelope’s total energy becomes positive. The value of λ is then larger than usually estimated by a factor of $\sim 2 - 5$, which might help allow for a low-mass ($\lesssim 1 M_{\odot}$) companion to survive from the CE phase, even if the primary star is initially as massive as $30 M_{\odot}$. There are arguments both for and against this “enthalpy” formalism from theoretical points of view, as outlined by Ivanova et al. (2013). Different formalisms of λ may be distinguished by applying them to the formation of specific binaries and comparing the results with observations⁴. Obviously a proper estimate of the energy requirement for the CE ejection is critical for the formation of not only BHLMBs but also all kinds of post-CE binaries.

Another important physical question in calculating E_{bind} is how to determine the boundary between the remaining “core” and the ejected “envelope” of the star. There are different definitions of the boundary in the literature, which are (1) related to the nuclear energy generation within the hydrogen burning shell, (2) based on the the hydrogen abundance, and (3) connected with thermodynamic quantities (Ivanova et al. 2013). Tauris & Dewi (2001) have shown that, depending on the definition of the core-envelope boundary and the treatment of the role of internal thermodynamic energy, the binding energy parameter λ can vary by two orders of magnitude (from 0.02 to 3.50) for the a $20 M_{\odot}$ star at the tip of red giant branch. This sensitivity results from the fact that the binding energy within the hydrogen burning shell greatly exceeds that of the outer convective envelope.

⁴When constructing the evolutionary history of IC 10 X–1, one of the three observed BH X-ray binaries that are known to host a Wolf-Rayet star as the mass donor (Clark & Crowther 2004), Wong et al. (2014) obtained constraints on the physics of the CE event, and found that the “enthalpy” formalism is the only one that can explain the existence of IC 10 X–1 without the need of invoking unreasonably high CE efficiencies α_{CE} . Unfortunately, the adopted $\sim 30 M_{\odot}$ BH mass is almost certainly incorrect, because it was derived from the radial velocity curve from the wind emission lines, under the unrealistic assumption that the wind is spherically symmetric (see van Kerkwijk 1993; Maccarone et al. 2014, for a discussion on this subject).

Ivanova (2006) suggested that every giant has a well-defined post-CE remnant after it has been thermally readjusted. The mass m_{cp} of the remnant is most likely given by the divergence point, which is best approximated by the point in the hydrogen burning shell that had maximal compression (local sonic velocity) prior to CE. If the remnant mass remains above or below m_{cp} , then the star expands to overflow its Roche lobe or contracts during its thermal readjustment. Thus m_{cp} could be regraded as the bifurcation point which defines where the spiral-in stops.

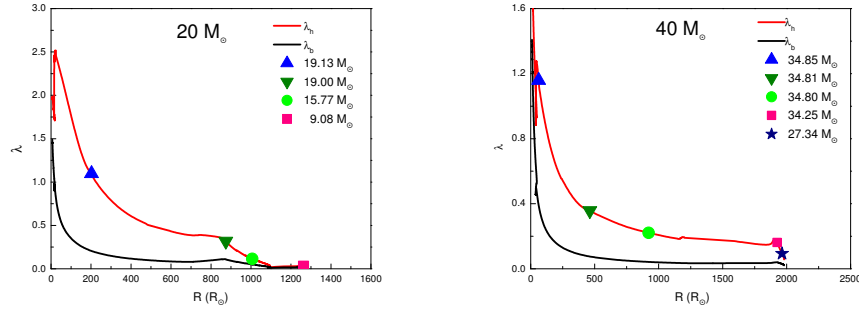


Figure 1: Dependence of the parameter λ on the stellar radius R for stars with initial mass of $20 M_{\odot}$ (left) and $40 M_{\odot}$ (right). The red and black lines denote λ with and without including the contribution of the P/ρ term (λ_h and λ_b , respectively) in the binding energy. Also shown are the stellar mass at different stages of the evolution.

If the orbit of the primordial binary is initially so wide that CE is initiated very late in the evolution of the primary star, the star may have lost most of its envelope in stellar winds, which means that there is not much orbital energy required for successful envelope ejection even with a low-mass companion star. Wiktorowicz, Belczynski, & Maccarone (2014) therefore argued that CE evolution is not crucial in the formation of Galactic BHLMXBs, and stars with mass $\sim 1 M_{\odot}$ are the most likely companions in BHLMXBs. It should be noted that this scenario may work for very massive primary stars, since the stellar wind prescriptions should not significantly affect the stellar structure and the compact object remnant masses for stars with initial mass $\lesssim 30 M_{\odot}$. It also requires that the progenitor binaries should have very wide orbits, so the parameter space for the formation of BHLMXBs could be quite small.

In Fig. 1 we compare the values of λ with and without including the contribution of the P/ρ term in the binding energy (denoted as λ_h and λ_b ,

respectively) as a function of the stellar radius (Wang & Li 2015, in preparation), adopting the core-envelope boundary suggested by Ivanova (2006). The left and right panels are for $20 M_{\odot}$ and $40 M_{\odot}$ stars, respectively. We also consider mass loss due to stellar winds as in Xu & Li (2010) (which is actually same as in Hurley et al. 2000), and denote the stellar mass during its evolution. It is seen that, in both cases, $\lambda_h \gtrsim 0.15$ for a rather wide range of stellar radius (except near the end of the evolution), while $\lambda_b < 0.15$ except for small radius.

3.3. Other models

Eggleton & Verbunt (1986) suggested that the progenitor of a BHLMBX is a triple star, in which a massive close binary is accompanied at a large distance by a low-mass star. After the evolution of the close binary into an ordinary X-ray binary, the compact object is engulfed by its expanding massive companion, and spirals in to settle at its center. The resulting Thorne-Żytkow object (TŻO, Thorne & Żytkow 1975, 1977) gradually expands until it attains the size of the low-mass star’s orbit. Then a second spiral-in phase ensues, leading to the formation of a low-mass close binary.

Podsiadlowski, Cannon, & Rees (1995) proposed that during the evolution of TŻOs the central NS may be converted into a BH by intense accretion, and part of the envelope may collapse into a massive disc, which may become gravitationally unstable and lead to formation of low-mass stars or planets. Further evolution would be similar as standard LMXBs.

Ivanova (2006) argued that some BHLMBXs could harbour pre-main sequence donors. For a binary with an extreme mass ratio, the primary star evolves rapidly to explode and create a BH, while its low-mass companion has not reached the zero-age main sequence at that time. As a pre-main sequence star usually possesses strong magnetic fields, during its contraction toward the main sequence, MB dissipates the orbital angular momentum, and drives mass transfer. Because pre-main sequence stars are cooler than main sequence stars, the temperature issue in the IMXB models would be avoided.

The aforementioned models can also explain the enhanced lithium abundance measured in several BHLMBXs (though in different ways), because either TŻOs provide an ideal environment for the production of ${}^7\text{Li}$ by the ${}^7\text{Be}$ -transport mechanism, or pre-main sequence stars can have high (up to primordial) Li abundance since no nuclear burning occurs in them. The predicted BHLMBXs should be young systems or subject to small kicks during

the formation of BHs, and therefore have relatively low space velocities and a very small Galactic scaleheight. However, none of the Galactic BH transients are associated with or found nearby star-forming regions. It is also difficult for these models to explain the spatial distribution BH binaries like GROJ1655–40 (Willems et al. 2005), XTE J1118+480 (Fragos et al. 2009) and MAXI J1659–152 (Yamaoka et al. 2012), which are thought to have received rather large kick velocities ($\sim 100 - 200 \text{ kms}^{-1}$) at birth. They might be suitable for V404 Cyg, which has a peculiar velocity of about 40 kms^{-1} (Miller-Jones et al. 2009), implying that its BH did not receive a velocity kick larger than this value.

4. Discussion and conclusions

BHLMXBs are exotic objects because they are very difficult to form; they are also fascinating objects because they offer the best opportunity to study not only astrophysical phenomena associated with extreme gravity, but also binary evolution and SN mechanisms. We have briefly reviewed the progress made over the past decade in theoretical investigations on the formation of BHLMXBs, in particular short-period systems. Understanding these binaries is difficult, since some fundamental issues have not been resolved, including

- (1) What is the mass range of the BH progenitor stars?
- (2) Do the mass gap in BHs really exist? If it does, what’s the physics behind it?
- (3) What is the distribution of the kick imparted on newborn BHs?
- (4) How to properly estimate the total binding energy within the stellar envelope during CE evolution? Do we really need an initially intermediate-mass companion star for BHLMXBs?
- (5) What’s the dominant mechanism of orbital angular momentum loss in BHLMXBs? How can it account for the rapid orbital decay found in XTE J1118+480 and A0620–00?

In a recent work, Kochanek (2014) suggested that stars of mass $16.5 - 25 M_{\odot}$, which have not been observed as the progenitors of Type IIP SNe, die in failed SNe. Such failed SNe eject their hydrogen envelopes in a weak transient, leaving a BH with the mass of the star’s helium core ($5 - 8 M_{\odot}$). This may explain the typical masses of observed BHs and the gap between NS and BH masses without any fine-tuning of stellar mass loss, or the SN mechanism. Compared with more massive stars, these stars have relatively

higher λ (see Fig. 1), which may also help eject the envelope for a low-mass companion star.

Obviously thorough population synthesis calculations are required to investigate the evolutionary history of BHLMBs by incorporating various factors aforementioned in a more self-consistent way.

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References

- Bailyn, C. D., Jain, R. J., Coppi, P., & Orosz, J. A. 1998, *ApJ* 499, 367
- Bardeen, J. M. 1970, *Nat*, 226, 64
- Belczynski, K., Wiktorowicz, G., Fryer, C. L., Holz, D. E., & Kalogera, V. 2012, *ApJ*, 757, 91
- Bhattacharya, D. & van den Heuvel, E. P. J. 1991, *Phys. Rep.*, 203, 1
- Braithwaite, J. & Spruit, H. C., 2004, *Nat*, 431, 819
- Casares, J. & Jonker, P. G. 2014, *Spa. Sci. Rev.*, 183, 223
- Charles, P. A. & Coe, M. J. 2006, Optical, ultraviolet and infrared observations of X-ray binaries. in *Compact stellar X-ray sources*, eds. W. H. G. Lewin and M. van der Klis, 215
- Chen, W., Shrader, C. R., & Livio, M. 1997, *ApJ*, 491, 312
- Chen, W.-C., & Li, X.-D. 2006, *MNRAS*, 373, 305
- Chomiuk, L., Strader, J., Maccarone, T. J. et al. 2013, *ApJ*, 777, 69
- Clark, J. S., & Crowther, P. A. 2004, *A&A*, 414, L45
- Davis, S. W., Blaes, O. M., Hubeny, I., & Turner, N. J. 2005, *ApJ*, 621, 372
- de Kool, M. 1990, *ApJ*, 358, 189

- Dewi, J. D. M., & Tauris, T. M. 2000, *A&A*, 360, 1043
- Dubus, G., Lasota, J.-P., Hameury, J.-M., & Charles, P. 1999, *MNRAS*, 303, 139
- Eggleton, P. P. & Verbunt, F. 1986, *MNRAS*, 220, 13
- Fabian, A. C. et al. 2014, *MNRAS*, 439, 2307
- Fabian, A. C., Rees, M. J., Stella, L., & White, N. E. 1989, *MNRAS*, 238, 729
- Farr, W. M. et al. 2011, *ApJ* 741, 103
- Fragos, T. & McClintock, J. E. 2015, *ApJ*, 800, 17
- Fragos, T., Willems, B., Kalogera, V. et al. 2009, *ApJ*, 697, 1057
- Fryer, C. L. 1999, *ApJ*, 522, 413
- Fryer, C. L. et al. 2012, *ApJ*, 749, 91
- Fryer, C. L. & Kalogera, V. 2001, *ApJ*, 554, 548
- Gallo, E., Migliari, S., Markoff, S. et al. 2007, *ApJ*, 670, 600
- Garcia, M. R., McClintock, J. E., Narayan, R. et al. 2001, *ApJ*, 553, L47
- Gelino, D. M., Harrison, T. E., & Orosz, J. A. 2001, *AJ*, 122, 2668
- González Hernández, J. I., Rebolo, R., & Casares, J. 2012, *ApJ*, 744, L25
- González Hernández, J. I., Rebolo, R., & Casares, J. 2012, *MNRAS*, 438, L21
- González Hernández, J. I., Rebolo, R., Israelian, G., 2007, *A&A*, 478, 203
- González Hernández, J. I., Rebolo, R., Israelian, G., Harlaftis, E. T., Filippenko, A. V., & Chornock, R., 2006, *ApJ*, 644, L49
- Gou, L., McClintock, J. E., Steiner, J. F. et al. 2010, *ApJ*, 718, L122
- Han, Z., Podsiadlowski, Ph., & Eggleton, P. P. 1994, *MNRAS*, 270, 121

- Haswell, C. A., Hynes, R. I., King, A. R., & Schenker, K. 2002, MNRAS, 332, 928
- Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
- Israelian, G., Rebolo, R., Basri, G., Casares, J., & Martin, E. L., 1999, Nat, 401, 142
- Ivanova, N. 2002, PhD thesis, Oxford University
- Ivanova, N. 2006, ApJ, 653, L137
- Ivanova, N. 2011, ApJ, 730, 76
- Ivanova, N. & Chaichenets, S. 2011, ApJ, 731, L36
- Ivanova, N. et al. 2013, A&AR, 21, 59
- Justham, S., Rappaport, S., & Podsiadlowski, P. 2006, MNRAS, 366, 1415
- Kalogera, V., 1999, ApJ, 521, 723
- Kiel, P. D., & Hurley, J. R. 2006, MNRAS, 369, 1152
- King, A. R. & Kolb, U. 1999, MNRAS, 305, 654
- King, A. R., Kolb, U., & Burderi, L. 1996, ApJ, 464, L127
- Kochanek, C. S. 2014, ApJ, 785, 28
- Kreidberg, L., Bailyn, C. D., Farr, W. M., & Kalogera, V. 2012, ApJ, 757, 36
- Kuulkers, E. et al. 2013, A&A, 552, A32
- Lasota, J.-P. 2001, NAR, 45, 449
- Li, X.-D. 2008, MNRAS, 384, L16
- Maccarone, T. J. 2014, Spa. Sci. Rev., 183, 101
- Maccarone, T. J., Lehmer, B. D., Leyder, J. C. et al. 2014, MNRAS, 439, 3063

- Martin, E. L., Casares, J., Molaro, P., Rebolo, R., & Charles, P. A. 1996, *New Astron.*, 1, 197
- Martin, E. L., Rebolo, R., Casares, J., & Charles, P. A. 1992, *Nat*, 358, 129
- Martin, E. L., Rebolo, R., Casares, J., & Charles, P. A. 1994, *ApJ*, 435, 791
- McClintock, J. E., Narayan, R., & Steiner, J. F. 2014, *Space Sci. Rev.*, 183, 295
- McClintock, J. E., Shafee, R., & Narayan, R. 2006, *ApJ*, 652, 518
- Miller, J. M. et al. 2013, *ApJ*, 775, L45
- Miller-Jones, J. C. A. et al. 2009, *MNRAS*, 394, 1440
- Moss, D. 1989, *MNRAS*, 236, 629
- Muno, M. P. & Mauerhan, J. 2006, *ApJ*,
- Nieuwenhuijzen, H. & de Jager, C. 1990, *A&A*, 231, 134
- Orosz, J. A., Bailyn, C. D., McClintock, J. E., & Remillard, R. A. 1996, *ApJ*, 468, 380
- Özel, F., Psaltis, D., Narayan, R., & McClintock, J. E. 2010, *ApJ*, 725, 1918
- Paczynski, B. 1976, in *IAU Symposium, Vol. 73, Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Mitton, & J. Whelan, 75
- Podsiadlowski, P., Cannon, R. C., & Rees, M. J. 1995, *MNRAS*, 274, 485
- Podsiadlowski, P., Ivanova, N., Justham, S., & Rappaport, S. 2010, *MNRAS*, 406, 840
- Podsiadlowski, P., Rappaport, S., & Han, Z. 2003, *MNRAS*, 341, 385
- Portegies Zwart, S. F., Verbunt, F., & Ergma, E. 1997, *A&A*, 321, 207
- Remillard, R. A., & McClintock, J. E. 2006, *ARA&A*, 44, 49
- Romani, R. W. 1998, *A&A*, 333, 583
- Spruit, H. C. & Taam, R. E. 2001, *ApJ*, 548, 900

- Strader, J., Chomiuk, L., Maccarone, T. J., Miller-Jones, J. C. A., & Seth, A. C. 2012, *Nat*, 490, 71
- Taamk, R. E. & Spruit, H. C. 2001, *ApJ*, 561, 329
- Taam, R. E. & Ricker, P. M. 2010, *NAR*, 54, 65
- Tauris, T. M., & Dewi, J. D. M. 2001, *A&A*, 369, 170
- Tauris, T. M. & van den Heuvel, E. P. J. 2006, in Lewin W., van der Klis M., eds, *Compact Stellar X-ray Sources*. Cambridge Univ. Press, Cambridge, p. 623
- Thorne, K. S. 1974, *ApJ*, 191, 507
- Thorne, K. S. & Żytkow, A. N. 1975, *ApJ*, 199, L19
- Thorne, K. S. & Żytkow, A. N. 1977, *ApJ*, 212, 832
- van den Heuvel, E. P. J. 1983, in *Accretion-driven stellar X-ray sources*, eds. W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge University Press), P. 303
- van den Heuvel, E.P.J. 1992, *Proc. Inter. Space Year Conf. ESA ISY-3*, p.29
- van Kerkwijk, M. H. 1993, *A&A*, 176, L9
- van Paradijs, J., 1996, *ApJ* 464, L139
- Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, *A&A*, 369, 574
- Webbink, R. F. 1984, *ApJ*, 277, 355
- Wijers, R. A. M. J., 1996, in Wijers R. A. M. J., Davies M. B., Tout C. A., eds, *Evolutionary Processes in Binary Stars*. Kluwer, Dordrecht, p. 327
- Wiktorowicz, G., Belczynski, K., & Maccarone, T. J. 2014, *ApJ* submitted (arXiv:1312.5924)
- Willems, B. et al. 2005, *ApJ*, 625, 324
- Wong, T.-W., Valsecchi, F., Ansari, A. et al. 2014, *ApJ*, 790, 119

- Wu, Y. X., Yu, W., Li, T. P., Maccarone, T. J., & Li, X.-D. 2010, *ApJ*, 718, 620
- Xu, X.-J., & Li, X.-D. 2010, *ApJ*, 716, 114
- Yamaoka, K., Ishikawa, T., Matsubaya, O. et al. 2012, *PASJ*, 64, 32
- Yungelson, L. R., & Lasota, J.-P. 2008, *A&A*, 488, 257
- Yungelson, L. R., Lasota, J.-P., Nelemans, G., et al. 2006, *A&A*, 454, 559
- Zhang, S. N., Cui, W., & Chen, W. 1997, *ApJ*, 482, L155